OPERATIONAL EXPERIENCES OF JET TRANSPORTS

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INTRODUCTION

Concurrent with the introduction of turbine-powered airplanes into commercial transport operations, the NASA initiated a systematic sampling program for collecting normal acceleration, airspeed, and altitude data from routine airline operations. These measurements are being utilized to provide statistical data on a number of operational aspects of the turbine-powered transports, such as the gust and maneuver accelerations experienced, the gust velocities encountered, the airspeed operating practices, and the performance during take-off and landing. This program is a continuation of the long-standing NACA/NASA effort in collecting operational data on commercial transport airplanes and is providing information on current operations similar to that summarized in reference 1 for piston-engine transports. In the past, information obtained from the data collection program has proved useful in three broad areas: (1) comparison of the operational experiences of the airplane with the concepts to which they were designed, (2) detection of new or unanticipated aspects of the operations, and (3) formation of a background of information for application to the design of new airplanes.

In this paper, the scope of the data collection program on turbine-powered transports will be outlined, the instrumentation will be briefly described, and the characteristics of the records obtained will be

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explained. Then, some of the data which have been obtained from jet transports will be presented. These data pertain to airspeed operating practices, gust and maneuver loads, vertical velocity at landing, autopilot induced oscillatory loads, and unusual flight occurrences. Rather than attempt to summarize all the data from the turbine airplanes, main reliance will be placed on the results obtained from one particular operation of a turbojet transport.

SCOPE OF PROGRAM

The scope of the program is indicated in figure 1 in terms of the types of airplanes involved, the number of airlines, the number of recorder installations, and the sizes of data samples collected to date. Four types of turbojet and three types of turboprop transports operated on 11 different airlines have been included in the program up to the present time.

The airplanes on which the 30 VGH recorders are installed are operated on both domestic and transoceanic routes selected so as to provide a representative sampling of United States airline operations. In addition, one foreign airline engaged in transoceanic operations is included in the program.

In general, a minimum sample of 1,000 flight hours of the VGH time-history records is sought from each airplane. The data samples available to date range from about 1,800 hours for the Viscount to about 10,000 hours for the Boeing 707. The data collection on the F-27 and

Viscount has been completed and collection on some of the other airplane types is nearing completion. The data collection on the CV-990 has just begun. As the present programs are phased out, it is planned to sample operations of other airplanes as they are introduced into service.

INSTRUMENTATION

The NASA VGH recorder (ref. 2) is being used to obtain the time-history records of indicated airspeed, pressure altitude, and normal acceleration. As shown in figure 2, the recorder consists of three parts: the recorder base, the film drum, and the accelerometer. The recorder base houses a timer, airspeed and altitude elements, and a galvanometer to take signals from the accelerometer pickup. The accelerometer pickup consists essentially of a cantilevered beam with strain gages mounted to detect deflections and a heater element to maintain the damping oil at the proper temperature. The film drum accommodates a 200-foot roll of 70-mm photographic paper and contains a motor to drive the paper at a constant speed. Normally a film speed of about 1/2 inch per minute is used. This speed gives about 80 hours recording time on 200 feet of paper.

The recorder base is generally installed in the airplane radio racks and the remote acceleration pickup is mounted as close to the airplane's center of gravity as practical. The airspeed and altitude elements are generally connected to the copilot's lines. The recorder weighs approximately 20 pounds and operates on 28-volt power.

The estimated accuracy of the recorder, assuming nominal reading errors, is: ±0.05g for acceleration; ±3 knots at 300 knots, ±5 knots at 100 knots; ±100 feet at 2,000 feet, and ±300 feet at 20,000 feet. These accuracy values do not include installation errors which normally are small at the higher airspeeds and altitudes and which can be corrected for at the lower airspeeds and altitudes where the errors may become of importance.

Figure 3 illustrates a VGH record and lists some of the types of information which may be evaluated. The records show a typical variation with time of the airspeed, altitude, and acceleration from take-off through the climb, cruise, descent, and landing phases of a flight. Downward deflection of the altitude trace indicates increasing altitude; increasing airspeed is indicated by upward deflection; and positive acceleration, by downward movement of the trace. Accelerations due to gusts, maneuvers, and to autopilot or airplane induced oscillatory motions are identified by characteristic responses of the three traces associated with each acceleration source. Some of the operational information which may be obtained from the three traces is listed below the record.

RESULTS

As a means of discussing some of the operational experiences of turbine-powered transports, results obtained for one type of turbojet airplane will be presented. In a number of instances the turbojet results are compared with corresponding results from operations of four-engine piston transports, which are used herein as a reference for past operational experience. Although the turbojet operation selected for present consideration is by no means unique, neither of course can it be called representative of all turbine transport operations. Consequently, in addition to discussion of the selected results, indications will be given as to how the experiences for other turbine operations compare with past operations.

Description of Turbojet Operation

The turbojet airplane on which most of the data are to be presented was engaged in an operation involving a combination of both transoceanic and domestic type operations. Figure 4 describes the operation in terms of the duration of flights and the altitudes flown. The lower plot shows the percent of the total flights which were of given durations. The plot shows that the flight lengths tended to fall into two groups: one with a mean of about 2 hours and the other with a mean of about $5\frac{1}{2}$ hours. The longer length flights were associated with the transoceanic portion of the operation, and the shorter lengths with the domestic portion. The overall average length of flight for the operation was 3.4 hours.

The upper plot of figure 4 shows the percent of the total flight time which was flown in each of the altitude intervals of 5,000 feet. The plot shows that approximately 60 percent of the total flight time was between 25,000 and 35,000 feet. The time flown at the lower altitudes (below 25,000 feet) is associated primarily with the climbout and descent phases of flight and to a small extent with cruising on the shorter flights. These distributions of flight lengths and altitudes are fairly typical of a number of the turbojet operations which have been sampled in the VGH program.

Airspeed Practices

In figure 5 the turbojet operational airspeeds are compared with the operational speed placards. The plot on the left shows the average indicated airspeed for each altitude interval of 5,000 feet. The curves show the normal-operating limit speed V_{NO} and the never-exceed speed V_{NE} up to the altitude where the airplane is Mach limited. Above this altitude the two placards for this airplane are equal and are called the normal-operating limit Mach number M_{NO} and the never-exceed Mach number M_{NE} (ref. 3). In brief, these placards indicate the maximum speeds to which the airplane may be operated safely within the concepts to which it was designed. The general philosophy is that the airplane will not be flown above V_{NO} or M_{NO} during normal operations, and not above V_{NE} or M_{NE} even under emergency conditions. In general, the results show that the margin between the average speeds and the placard speeds decreases with increasing altitude up to the altitude where the airplane is Mach limited and is roughly constant above this altitude. At these high altitudes, the margin between the average speeds and the placard speeds is about 25 knots, whereas at the lower altitudes the margin is several times as large.

The plot on the right in figure 5 compares the airspeed practices of the turbojet with the average for past operations of four-engine piston airplanes. The curves show the percent of the total flight time that the airplanes were operated above given fractions of the normal-operating limit speed V_{NO}. The results show that the turbojet generally operates closer to the placard speed than did the piston transports. Also, the figure shows that the turbojet is operated in excess of the placard V_{NO} speed more frequently than was the experience with the piston transports. This result is typical of results obtained for other turbojets and also turboprop airplanes.

In order to examine the overspeeds in more detail, figure 6 shows the maximum airspeed and the altitude associated with each exceedence of the placard speed recorded during 150 flights of the turbojet. The results are shown for the three flight conditions: climb, cruise, and descent. The figure shows that most of the overspeeds occurred during the descent and that they are almost entirely in the lower altitudes where the airplane is limited by dynamic pressure considerations. Detailed examination of the time-history records has shown that the overspeeds during climb occur when the airplane is occasionally leveled off for short periods without reducing power. Similarly, the overspeeds in descent result when the airplane starts descending without prior reduction of power. The present results are typical of most of the turbojet operations sampled. For turboprop airplanes, overspeeds occur in both the dynamic pressure and Mach limited altitudes and also during the cruise portion of flight (ref. 4).

The overspeed problem with the turbine transports apparently results from a number of causes: (1) The high-performance capabilities of the airplanes which permit them to operate close to the placard speeds, (2) lack of appreciation by some operators and pilots as to the meaning and significance of the placard speed limit, (3) conflicting interpretations of the placard speeds in the Civil Air Regulation, and (4) overspeed warning devices either not being required or not being set to give adequate warning of overspeed condition. Inasmuch as the overspeed problem has implications as regards the establishment of design and operational speed margins for future airplanes, it has received widespread consideration by operators, manufacturers, and government agencies. In an attempt to alleviate the overspeed problem, the Federal Aviation Agency has proposed new Civil Air Regulations (ref. 5) which would institute a single speed placard for the present dual placards, clarify the meaning of the placard, and revamp the requirements for overspeed warning devices. Continued study of the airspeed practices will be required to determine the effectiveness of the new regulations in reducing the overspeeds and to provide information applicable to future designs.

Amount of Rough Air

Figure 7 shows the percent of the flight time in each altitude interval of 5,000 feet which was spent in rough air. For comparison with the turbojet data, the generally accepted variation of the amount of rough air with altitude as given in NACA TN 4332 (ref. 6) is shown by the curve. Both the turbojet data and the reference curve are based on a gust-velocity threshold of about 2 feet per second. The turbojet data are in excellent agreement with the earlier estimate at altitudes below 25,000 feet. Above this altitude the turbojet encountered rough air a smaller percent of the time than would be anticipated based on the reference results. It should be mentioned, however, that the intensity of the rough air encountered by the turbojet at the higher altitudes was somewhat more severe than estimated in NACA TN 4332. This combination of a smaller amount of rough air than expected but of increased intensity resulted in the overall gust-velocity history being close to previous estimates.

Gust Accelerations

The gust-acceleration history for the turbojet airplane is shown in figure 8 in terms of the average number of accelerations per mile of flight which exceeded given values. (All accelerations discussed herein are increments from the normal 1 g acceleration.) The two dashed lines in the figure show the range of the gust-acceleration histories for four-engine piston transports (ref. 1). The gust-acceleration history for the turbojet is approximately the same as the lower limit, or least severe curve, for the piston transports. Although this particular turbojet operation is about as smooth as any of the operations that have been sampled, the acceleration experiences for the turbine-powered transports lie mostly in the lower half of the band shown for the piston transports. In some particular operations involving turboprop airplanes engaged in feeder-line and short-haul operations, however, the acceleration experiences are more severe than the upper limit of the piston data. In general, though, it appears that from the turbulence aspects the turbojet and most of the turboprop transports achieve the increased passenger comfort which had been anticipated for the turbine airplanes.

Gust-Velocity Experience

The overall distribution of gust velocities encountered in the turbojet operation is shown in figure 9. For comparison, the upper and lower limits of corresponding results from piston transports are shown in the figure. The values of gust velocity were derived from the acceleration, airspeed, and weight data by the method described in reference 7. The results show that the gust-velocity distribution for this turbojet operation lies near the lower limit of the piston experience. In general, the gust-velocity experience for the turbine-powered transports has been found to be in fair agreement with estimates based on the turbulence model presented in NACA TN 4332 (ref. 6).

Maneuver Accelerations

The distribution of maneuver accelerations experienced during operational passenger-carrying flights is compared in figure 10 with corresponding results from piston transports. For this operation the operational maneuver experience is quite comparable to the piston airplanes experience. In the case of a number of other turbine transports, however, the operational maneuvers have been found to be more severe than the upper limits shown for the piston transports. For many of the turbine operations, it appears that the increased operational maneuvers detract from the passenger comfort and also tend to increase the number of fatigue loadings.

The distribution of maneuver accelerations experienced during airplane and pilot check and training flights is shown in figure 11 together with comparable piston airplane results. Over most of the acceleration range, the turbojet experience is more severe than the upper limit of the piston transport results. A tendency for the turbine transports to have a more severe check-flight maneuver experience has been noticed in a number of operations involving both turbojet and turboprop airplanes. This increased check-flight maneuver experience results not so much from more severe maneuvers, but rather because the turbine transports generally spend a larger percentage of their total flight time in pilot or airplane check flights than did the piston airplanes. In comparison with past operations, therefore, it appears that check-flight maneuvers are becoming of more importance in the airplane load history and may require increased consideration from the structural fatigue standpoint.

Oscillatory Accelerations

From VGH records collected on the turbine-powered transports, it has been observed that each type of airplane on occasion experiences oscillatory motions in the longitudinal or the longitudinal-lateral modes. Figure 12 shows the character of some of the oscillations which have been recorded in the present turbojet operations. The figure shows reproductions of three portions of VGH records containing oscillatory motions as evidenced by the acceleration traces. The upper record shows an oscillation of about 2 minutes duration wherein the magnitude of the accelerations reached about ±0.8g. Altitude deviations associated with this oscillation were ±300 feet. The period of this oscillation was approximately 20 seconds. At the time the oscillation began, the altitude was 33,000 feet and the Mach number was 0.87, which was very close to the never-exceed placard Mach number. It is suspected that the airplane was operating at this time on the edge of the buffet boundary and that this condition precipitated the rather severe oscillation. A number of similar oscillations have been observed on other turbojet transports.

The center record shows an oscillation lasting for about 3/4 minute and having amplitudes of about ±0.3g. Oscillations of this type have been observed frequently on the turbine transports. The lower record shows a continuous oscillation with a period of about 8 seconds and of amplitudes of about ±0.1g. Oscillations of this general type have been observed to continue for periods up to several hours.

Oscillations such as shown in figure 12 occur primarily during the cruise portion of flight, although they have been noted occasionally during climb and descent. In general, the oscillations occur randomly and do not appear to be associated with any particular airspeed-altitude combination. The oscillations have been recorded with and without the autopilot in operation, although most of the instances apparently occurred with the autopilot engaged. The percent of the total flight time that oscillations occur ranges from less than 1 percent on some airplanes to more than 30 percent for others.

Reported causes of the oscillations have included malfunctioning of autopilots due to such items as mismatched pitch accelerometers, vertical gyroscope malfunctions, air data computer malfunction, improper autopilot engagement, control system friction, and play in the control linkages. Also, oscillations have been induced when the airplane was operated on the edge of the buffet boundary. The oscillatory accelerations were not common to the piston transports, but are evidently widespread within the turbine fleet.

It is thought that the oscillatory loadings of the level presently being experienced would not have a major effect on the fatigue life of the airplane structure except in isolated cases, but that they may result in excessive loadings and wear in certain control system components. Although some passenger and crew complaints about the oscillations are known, the oscillations in general do not appear to cause widespread discomfort or body fatigue. The significance of the oscillations lies in the fact that they do constitute a new and additional source of airplane loadings which cannot be ignored, but which has to be avoided if possible and, if not, at least controlled within acceptable limits. In general, the oscillations are felt to be part of the price being paid for today's high-performance airplanes with their sophisticated control and autopilot systems which appear to be quite intolerant of off-optimum adjustment and tuning.

Comparison of Load Sources

A comparison of the turbojet in-flight accelerations due to various sources (check-flight maneuvers, operational maneuvers, gusts, and oscillatory motions) is given in figure 13. For accelerations greater than about 0.3g, check-flight maneuvers are seen to be the predominant load source, with gusts being the secondary source. At the lower values of accelerations (<0.3g), gusts tend to be the primary source, followed closely by check-flight and operational maneuvers.

For this particular turbojet, oscillations contributed a relatively small percentage of the total flight loads. For other airplanes, however, the position of the oscillatory acceleration curve may move up or down depending upon the prevalence of the oscillations on the particular aircraft. On some airplanes, the contributions of the oscillations to the total in-flight loads is substantially greater than is indicated for the present turbojet.

For past piston transports the primary in-flight acceleration source was gusts, with check-flight maneuvers being the secondary source for accelerations larger than about 0.3g. The reversal of this situation for the turbojet is due to a combination of two effects. First, the gust-acceleration curve for the turbojet has moved down relative to its position for the piston transports and, secondly, the check-flight maneuver curve for the turbojet has moved up relative to the piston results. These two trends have resulted in the check-flight maneuvers becoming, over much of the acceleration range, the major in-flight load source for the turbojets. Thus, for these types of airplanes the operational practices as concerns check flights take on an increased importance relative to piston transports for which the natural gust environment was the primary source of in-flight fatigue loads. For the turboprop airplanes, however, gusts continue to be the predominant source of in-flight loads both from fatigue and limit load considerations.

Vertical Velocity at Landing

Figure 14 presents information on the vertical velocities at landing contact for the type of turbojet considered herein. For comparison, the shaded area represents the range of results for past piston transport operations. Both the turbojet and piston airplane data were measured by a ground-based camera technique (refs. 8 and 9). The results show that, on the average, the vertical velocities for the turbojet are roughly 25 percent higher than for the piston airplanes. Other turbojets also exhibit this same tendency towards higher sinking speed. Inasmuch as both the turbine-powered and piston transports are designed to the same limit vertical velocity (10 fps), the increased vertical velocities of the turbojet tend to eat into some of the design margins enjoyed in past operations.

The increased vertical velocities at landing are of concern both as regards present airplanes and also because of possible implications concerning future advanced configurations such as the supersonic transport. Because of this concern, a number of investigations have been aimed at determining the reasons for the increased velocities and to provide a basis on which to estimate landing experiences for future airplanes. These investigations have included simulator studies and correlation studies of various airplane aerodynamic and configuration parameters. None of these studies have been successful in defining the critical factors affecting the velocities as yet, and work toward this end is continuing.

Unusual Events

From inspection of VGH records it has been observed that turbine transports experience unusual flight situations, usually involving high accelerations or abrupt airspeed and altitude changes, much more frequently than was the case with piston transports. An example of one such event involving a turboprop airplane is shown in figure 15. For clarity, the three VGH traces (acceleration, altitude, and airspeed) have been separated in the figure.

The time histories in figure 15 show that approximately 2 minutes after take-off, a rather abrupt maneuver was performed which resulted in an incremental acceleration of about 1.7g, or slightly over the design limit load factor increment. At the time, the airplane was at about 3,000 feet and climbing at a speed of about 220 knots. The maneuver resulted in a rapid loss of airspeed (about 25 knots) and an increased rate of climb. The remainder of the flight appeared to be normal.

Although no information concerning this incident could be obtained, it is thought that it may have been due to a collision avoidance maneuver.

The in-flight incident shown in figure 15 is only one of the many unusual occurrences which have been observed. Others involve extremely high speeds, high load factors, and precarious flight paths near the ground. In general, it is not possible to categorize these incidents and, in addition, flight crew information concerning the incidents usually is not obtained. It is difficult, therefore, to define the overall implications of these incidents. It is thought, however, that they are a manifestation of the greater complexity of the current transports, their higher speeds, and the increased traffic density.

CONCLUDING REMARKS

Time-history records of airspeed, altitude, and normal acceleration collected on turboprop and turbojet commercial transports are providing information concerning a number of operational aspects of these types of airplanes. The information available to date indicates that, in comparison with piston transports, the turbine transports exceed their placard speeds more frequently, generally are subjected to more maneuvers during check flights, and are involved more often in unusual flight situations. Also, the turbine transports frequently experience oscillatory motions apparently arising in a majority of the cases from the autopilot or control system. In addition, the turbojets experience vertical velocities at landing impact considerably higher than those associated with past operations.

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A/C TYPE	NO. A/C INSTRUMENTED	NUMBER AIRLINES	SAMPLE SIZE, HRS
707	9	4	9986
DC-8	7	4	6422
CV880	3	2	2491
CV990	2	1	0
ELECTRA	6	3	6266
F-27	2	1	2029
VISCOUNT	1	1	1838
TOTAL	30		29,032

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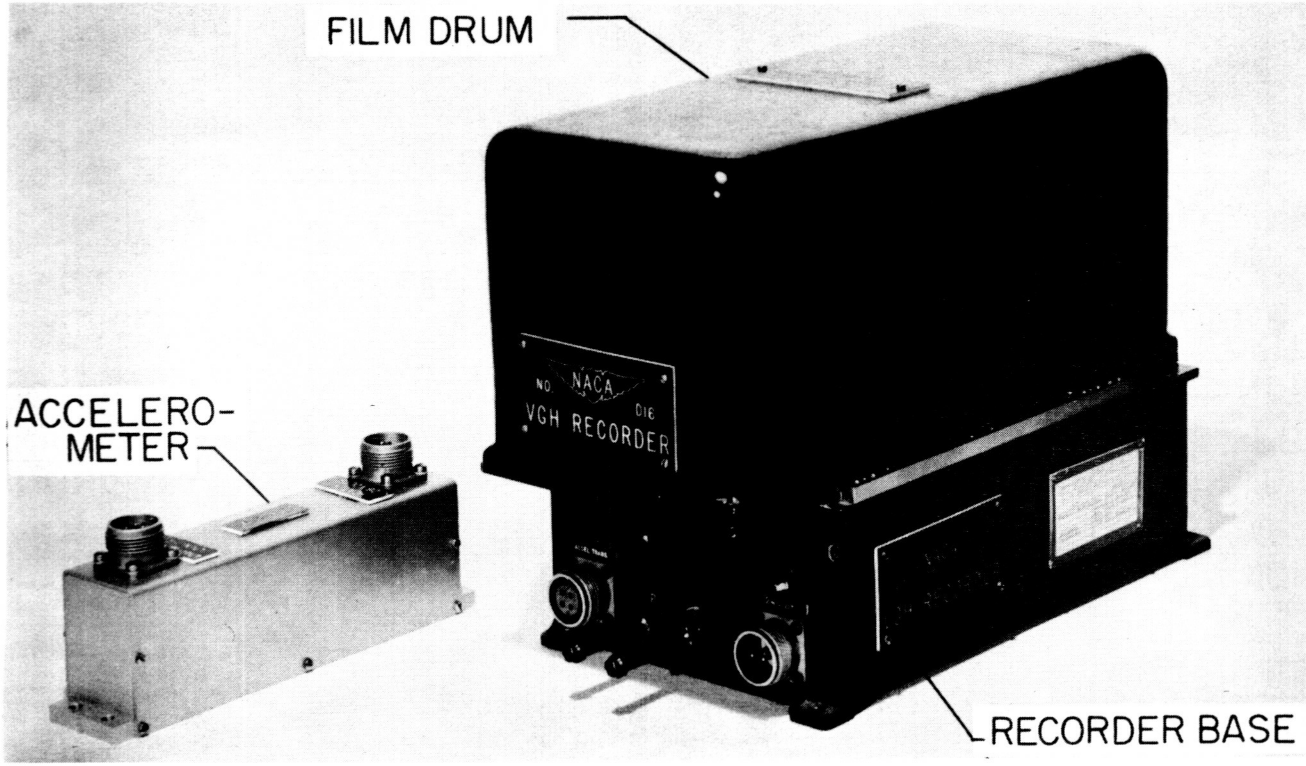
Figure 1.- Scope of VGH program.



OVERALL ACCURACY

ACCELERATION	— ± .05 g	
AIRSPEED	— ± 2.5 KNOTS	AT 250 KNOTS
	— ± 5 KNOTS	AT 100 KNOTS
ALTITUDE	— ± 300 FT	AT 20,000 FT
	— ± 150 FT	AT 2,000 FT

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Figure 2.- VGH recorder and accuracy.

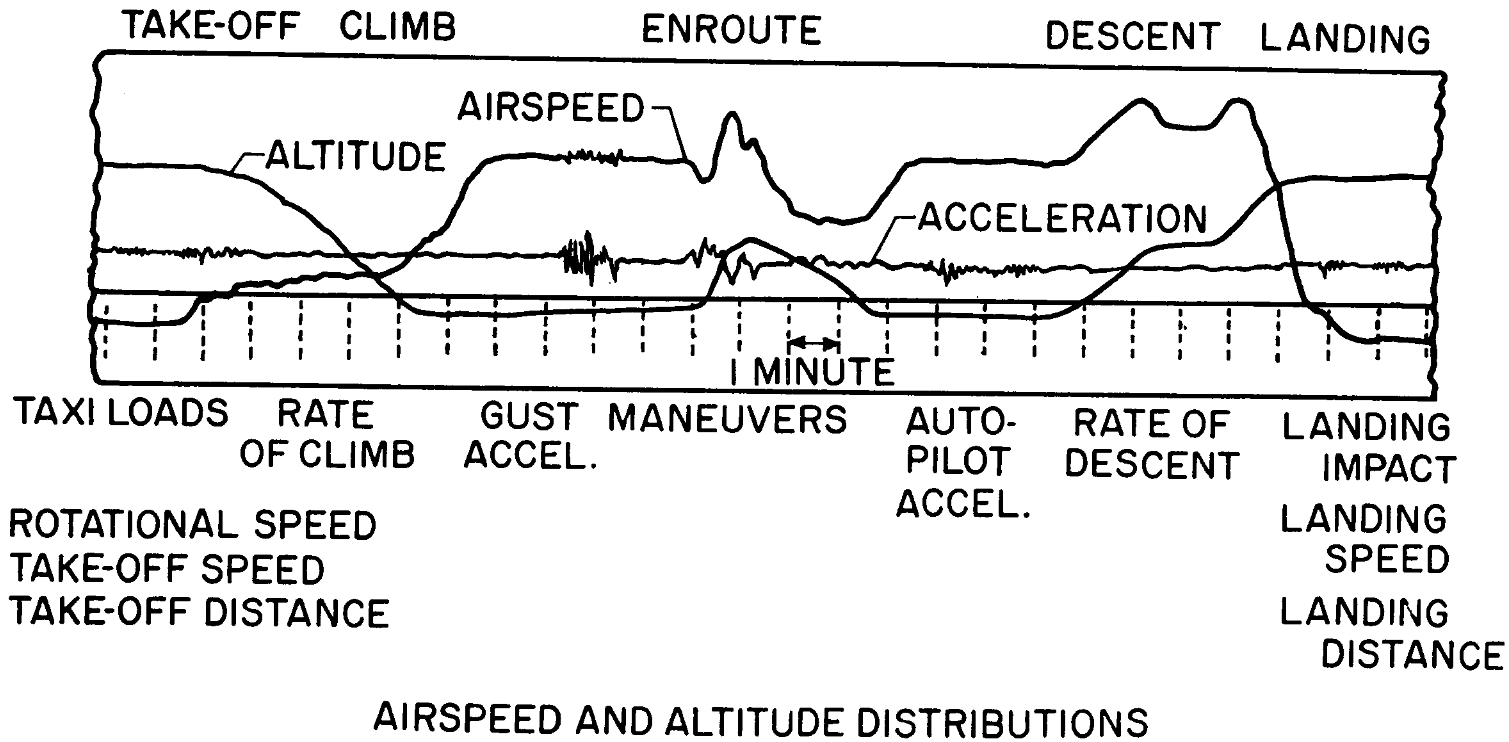

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Figure 3.- Illustrative VGH record and flight information obtained.

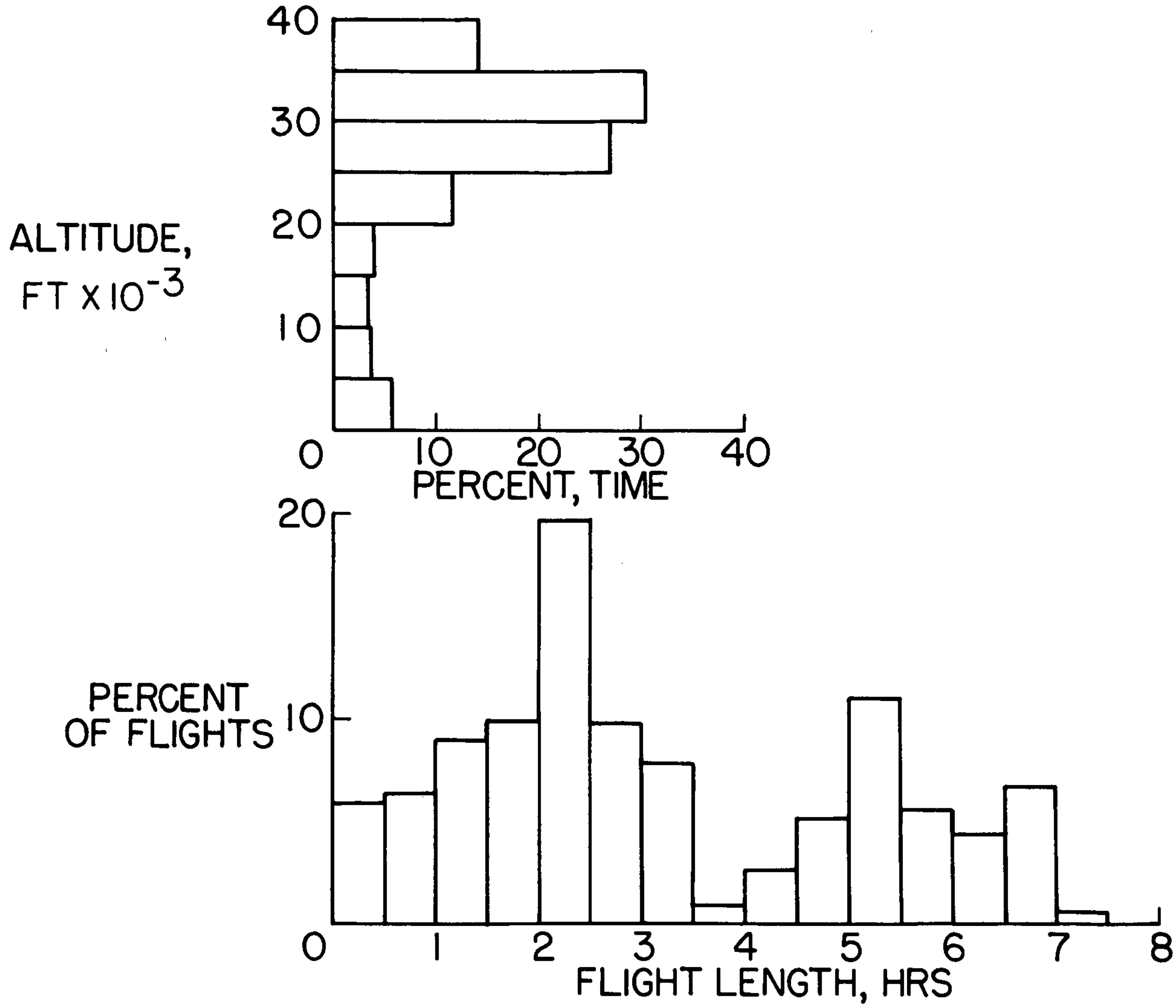

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Figure 4.- Description of turbojet operations.

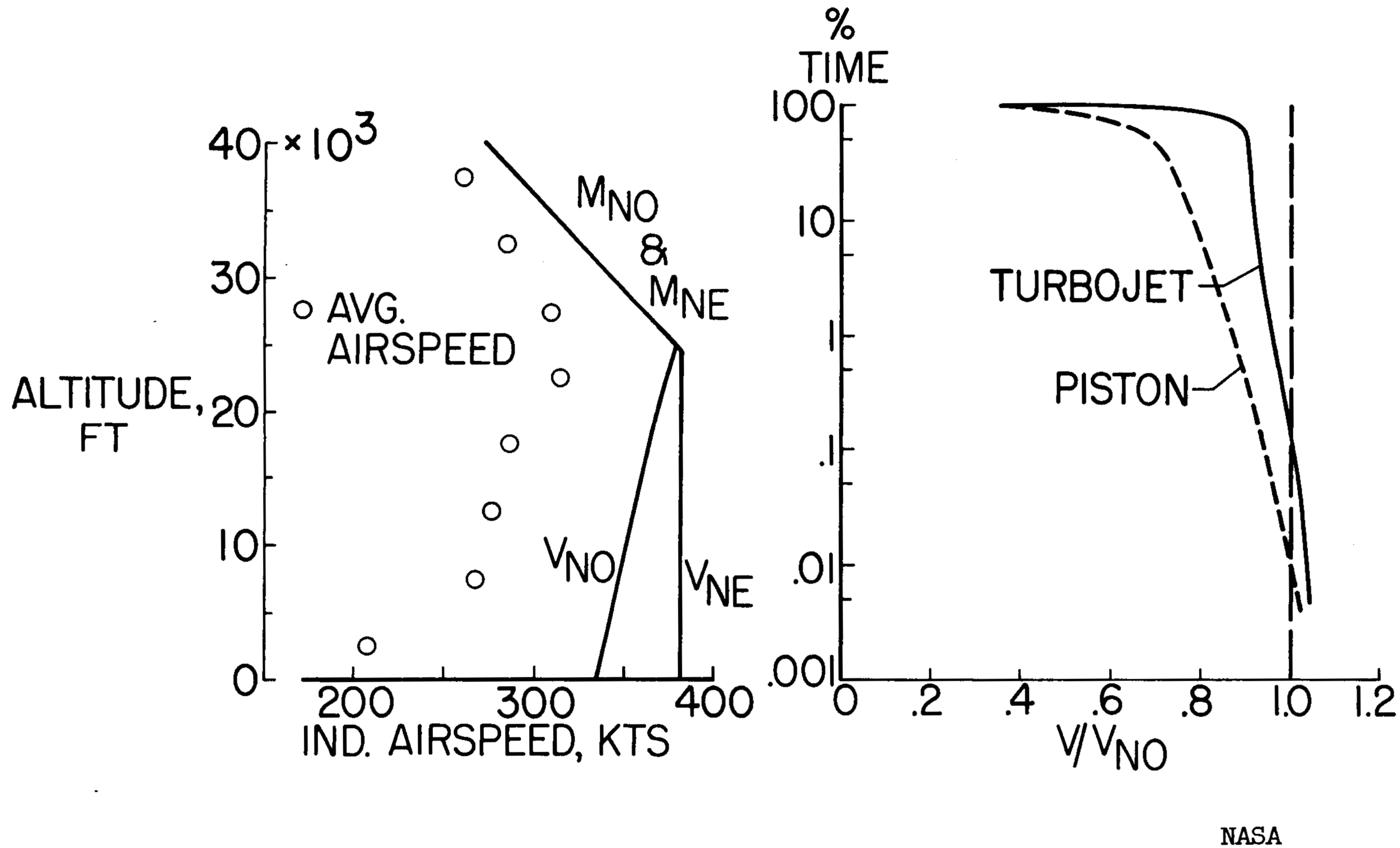

Figure 5.- Turbojet airspeed practices.

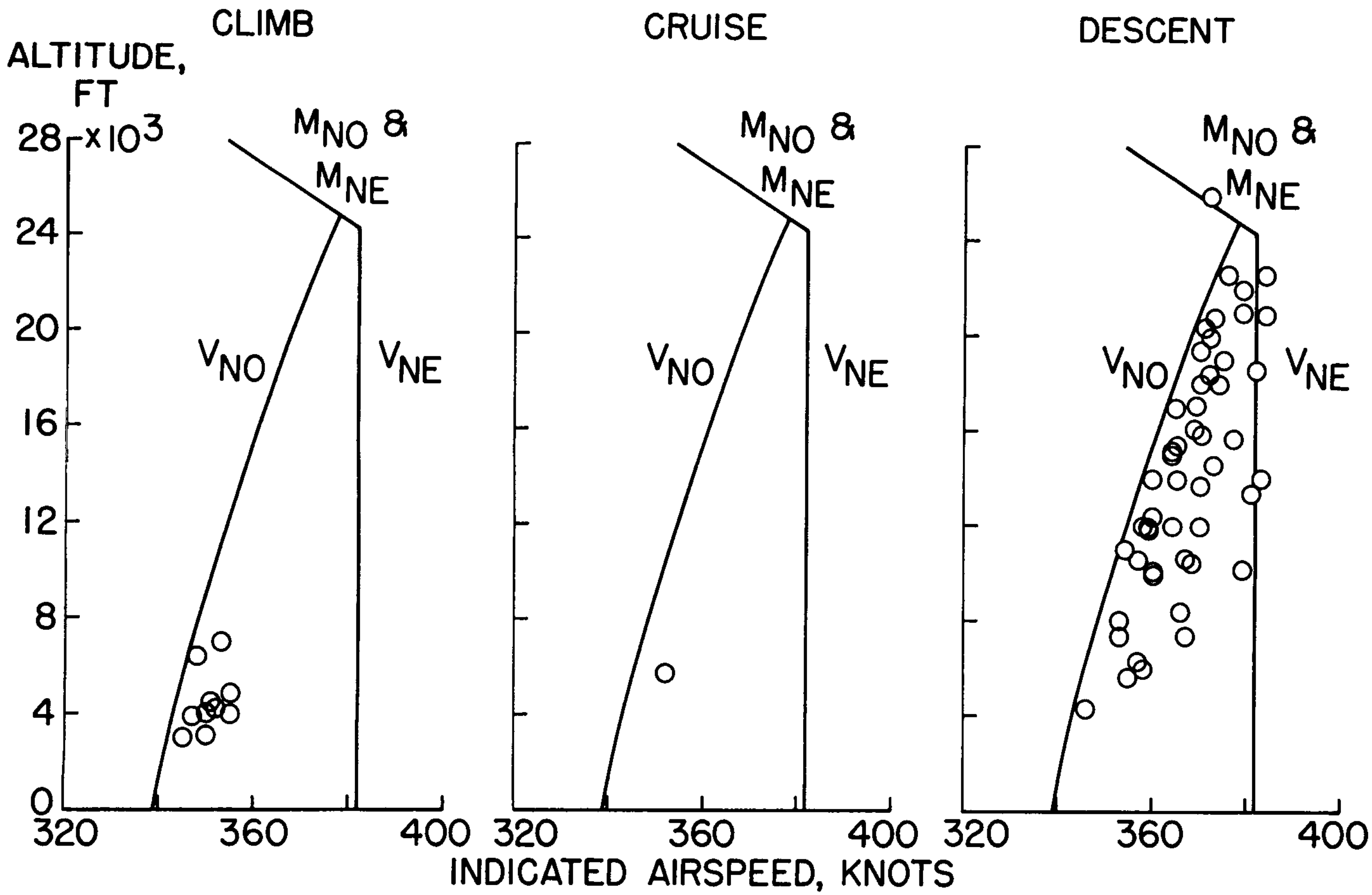

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Figure 6.- Placard speed exceedences.

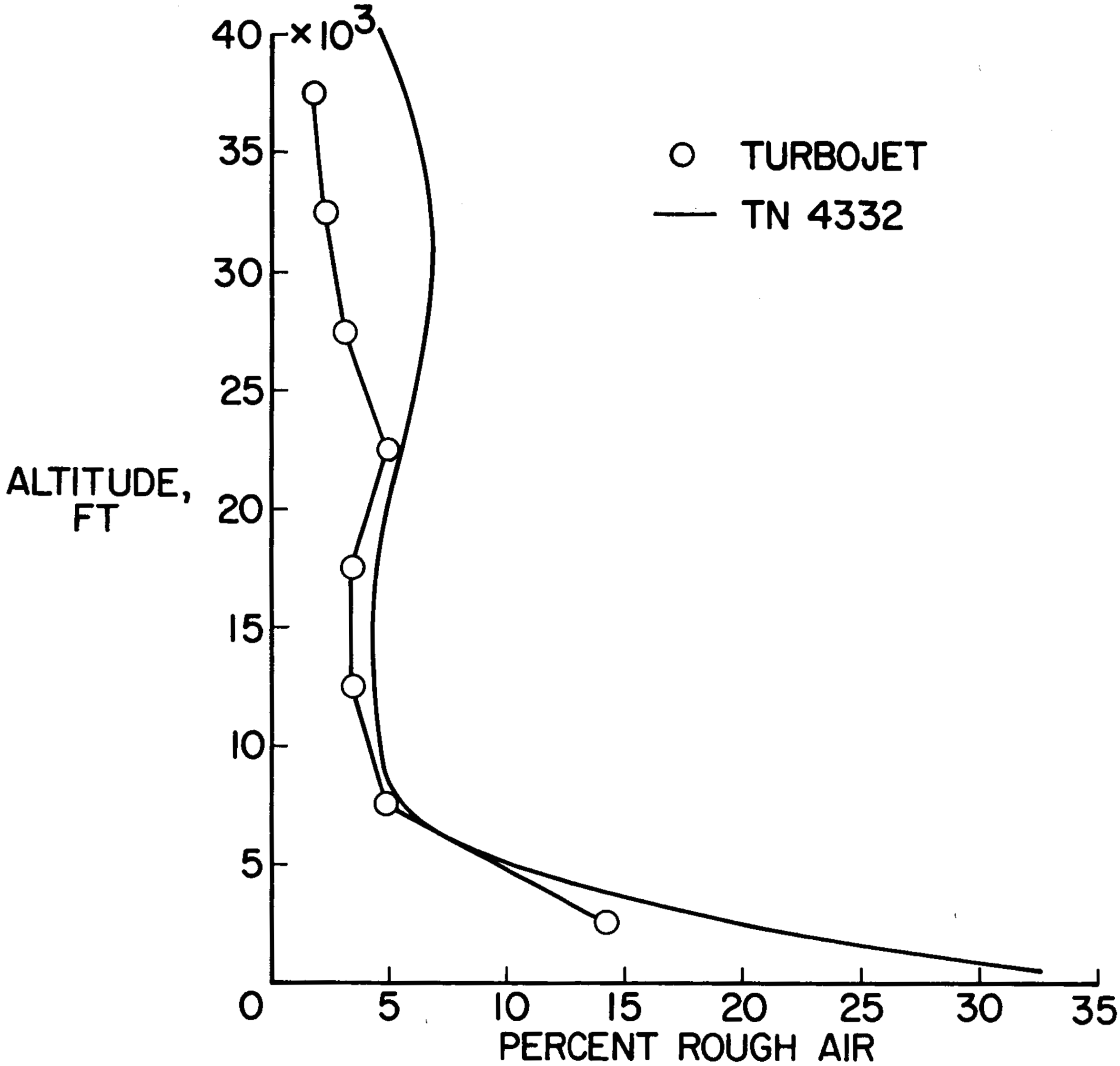

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Figure 7.- Variation of percent rough air with altitude.

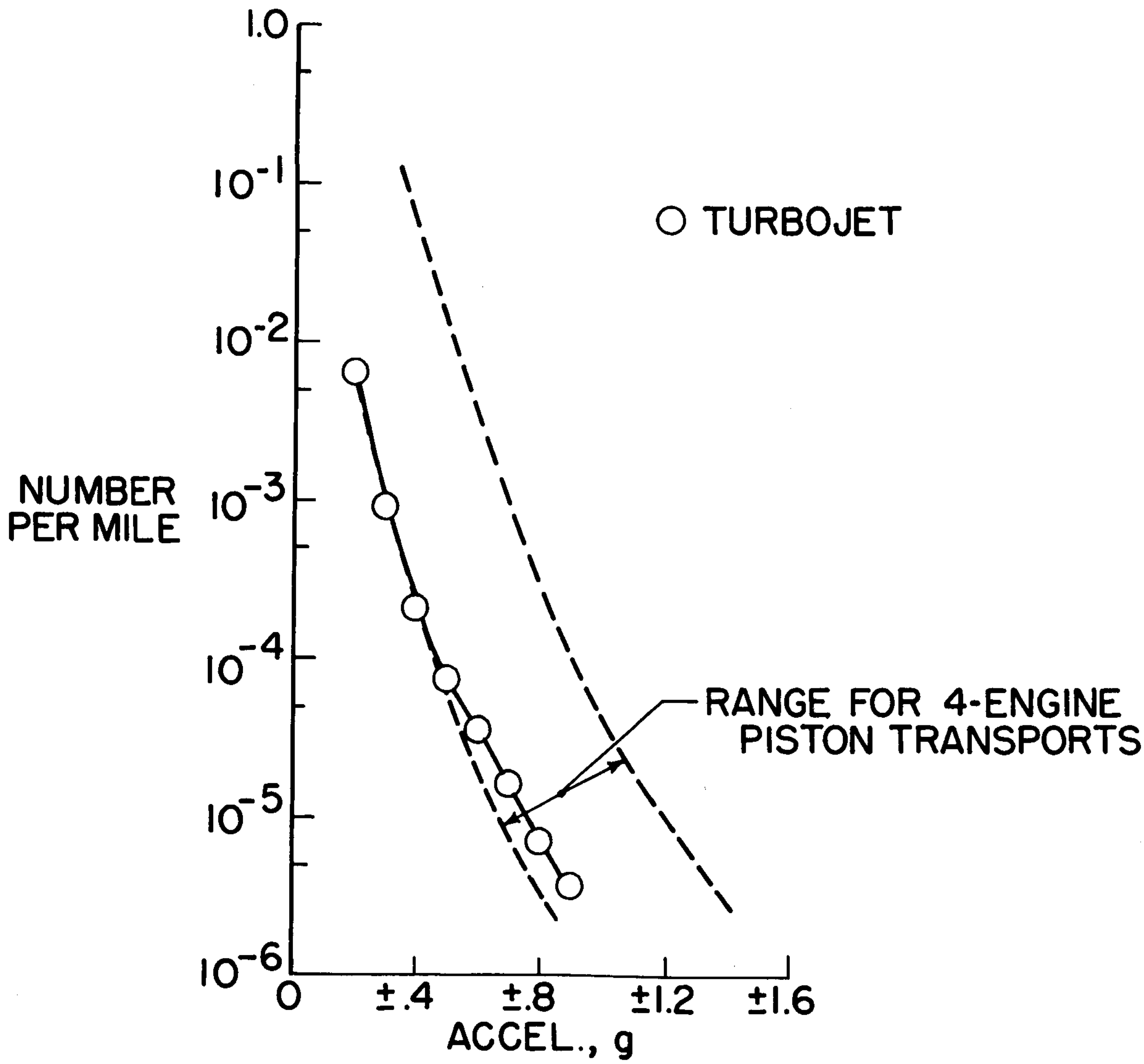

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Figure 8.- Gust acceleration experience.

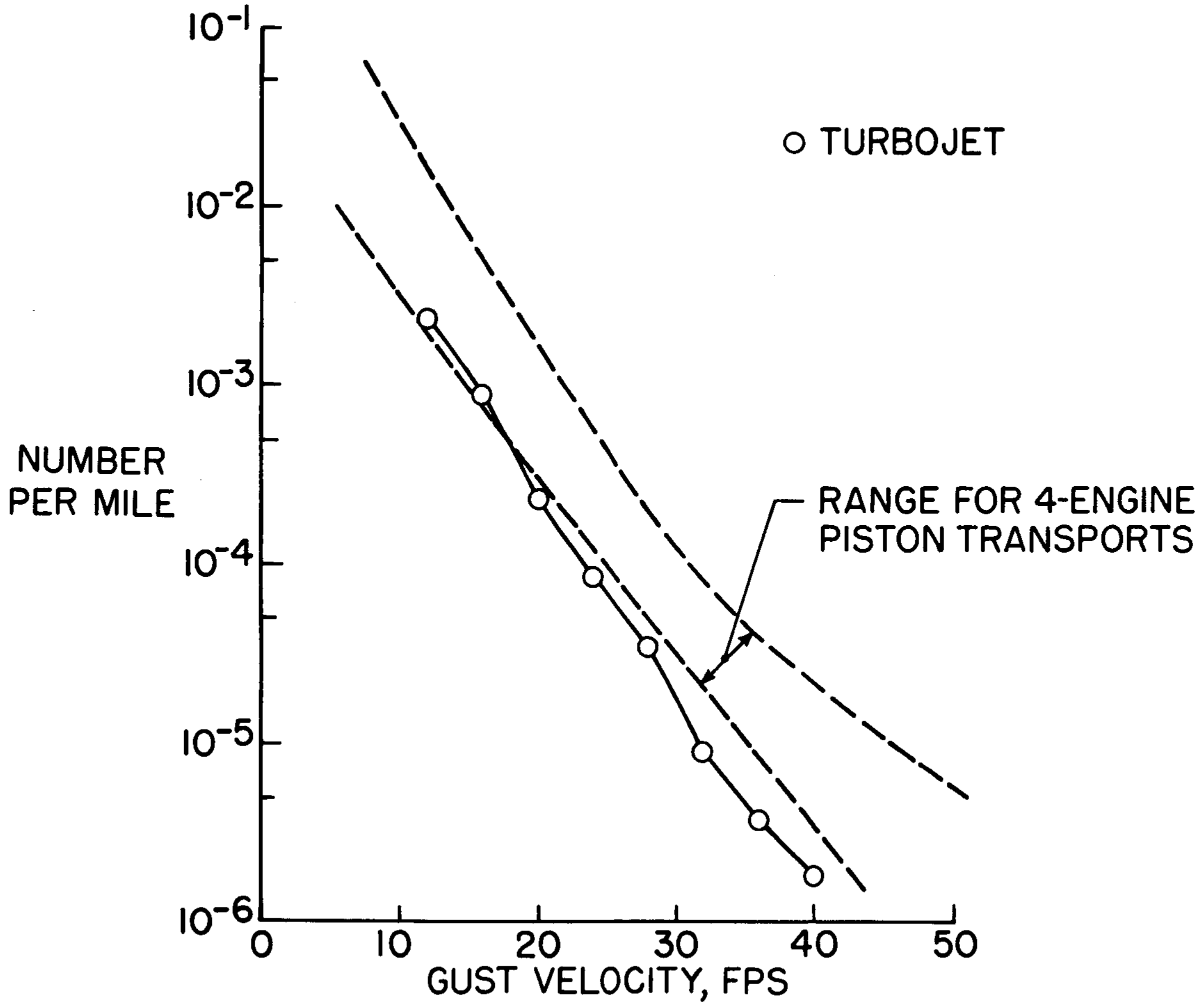

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Figure 9.- Gust velocity experience.

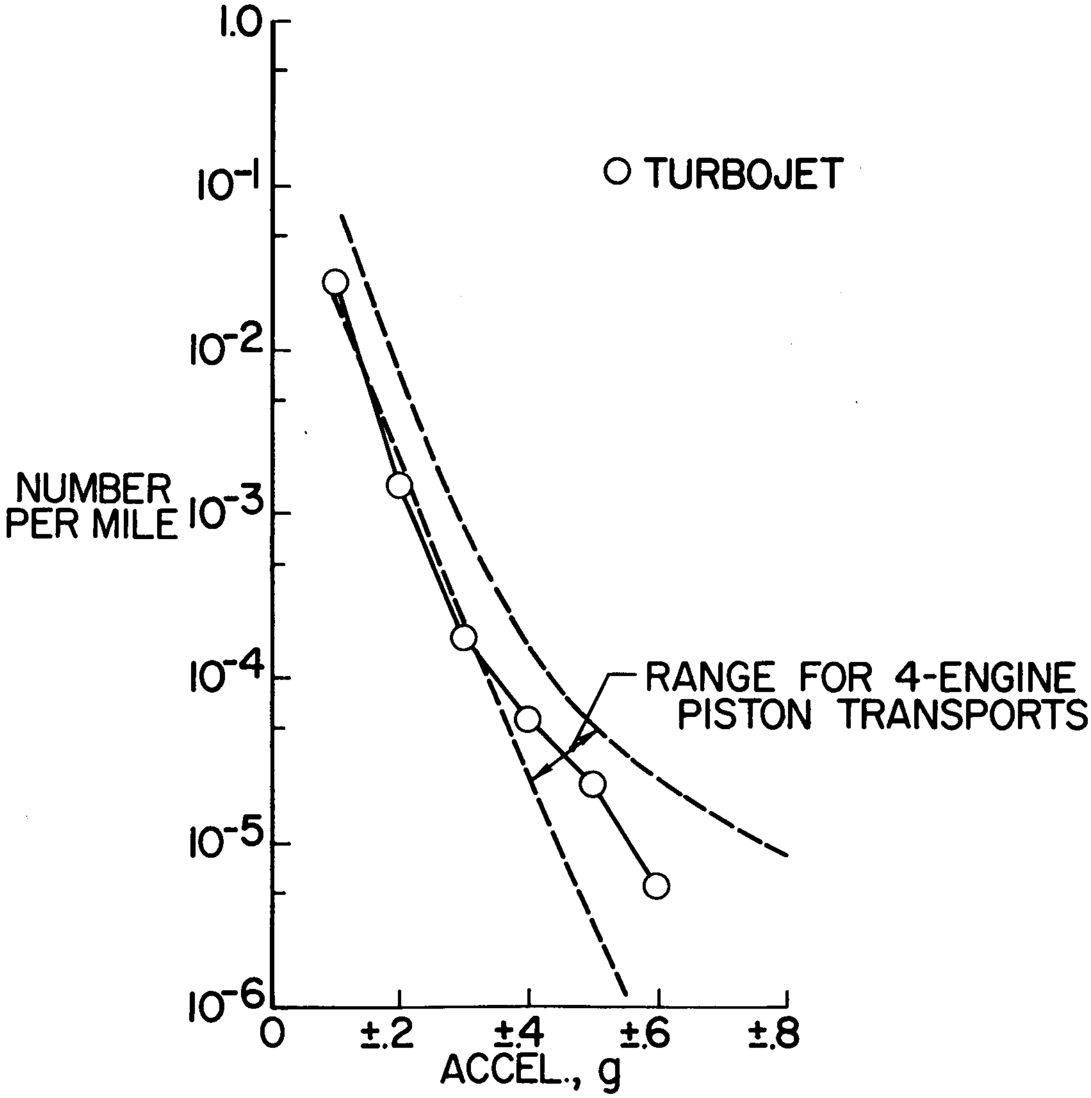

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Figure 10.- Operational maneuver experience.

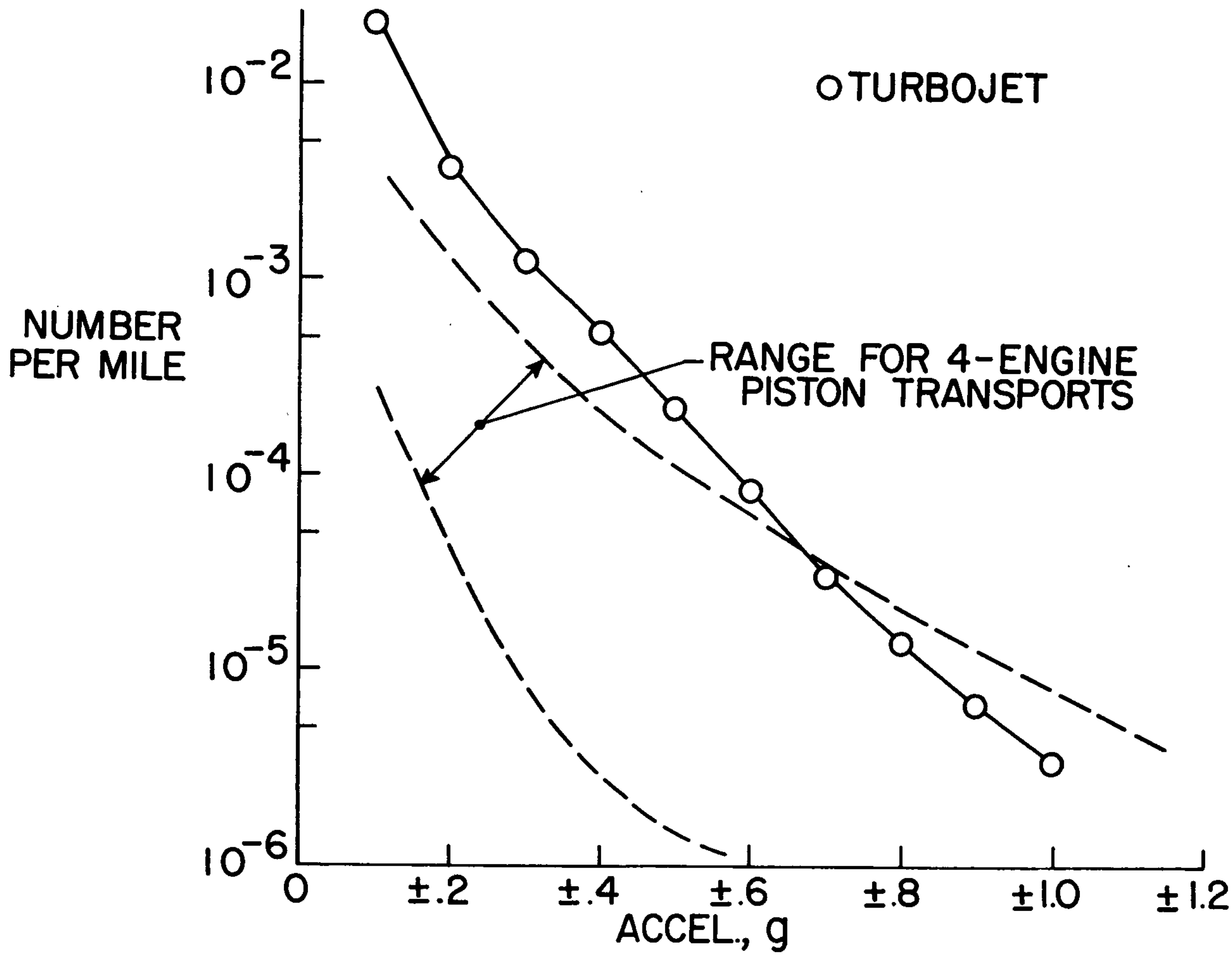

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Figure 11.- Check flight maneuver experience.

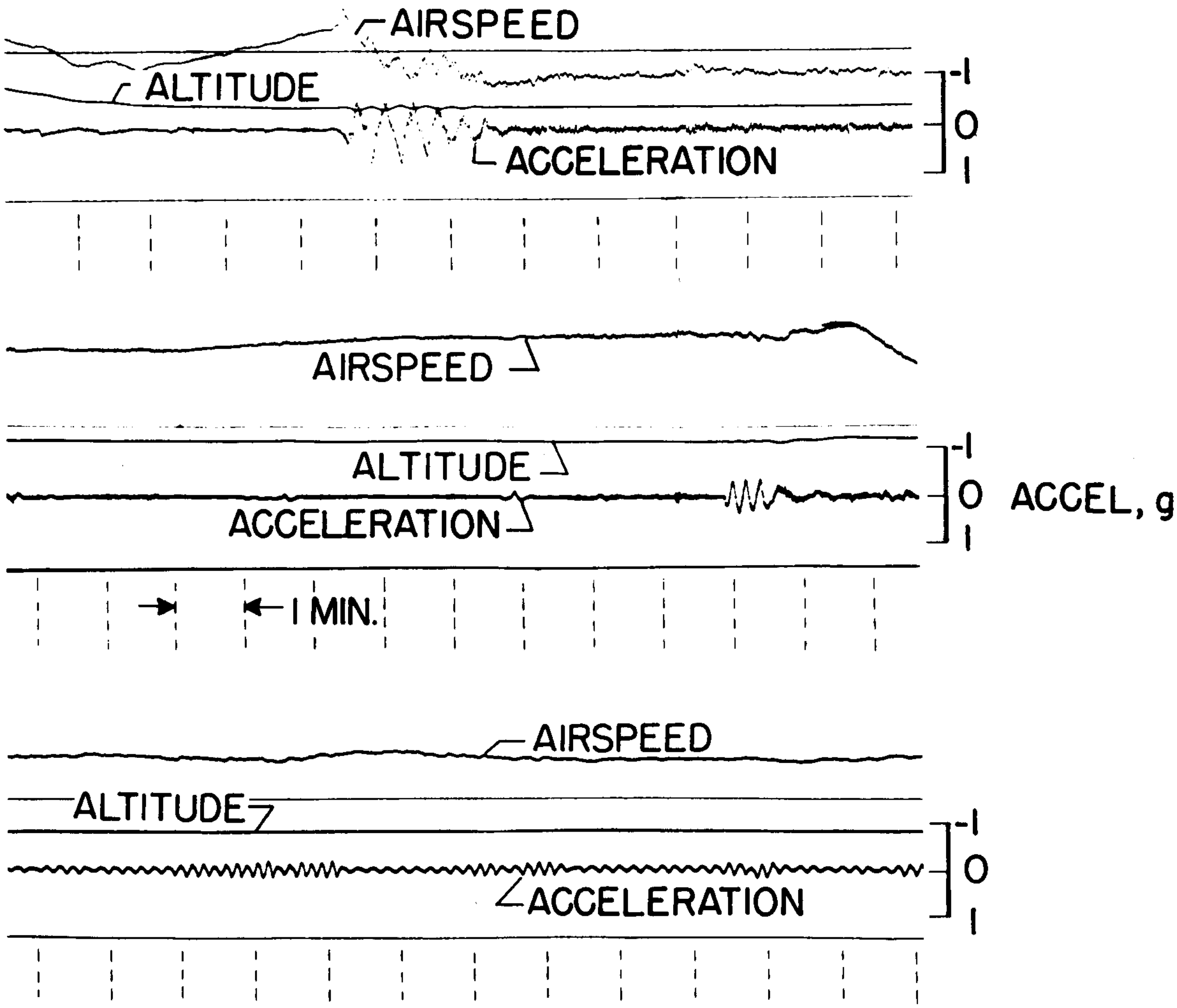

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Figure 12.- Examples of oscillatory accelerations on a 4-engine turbojet transport airplane.

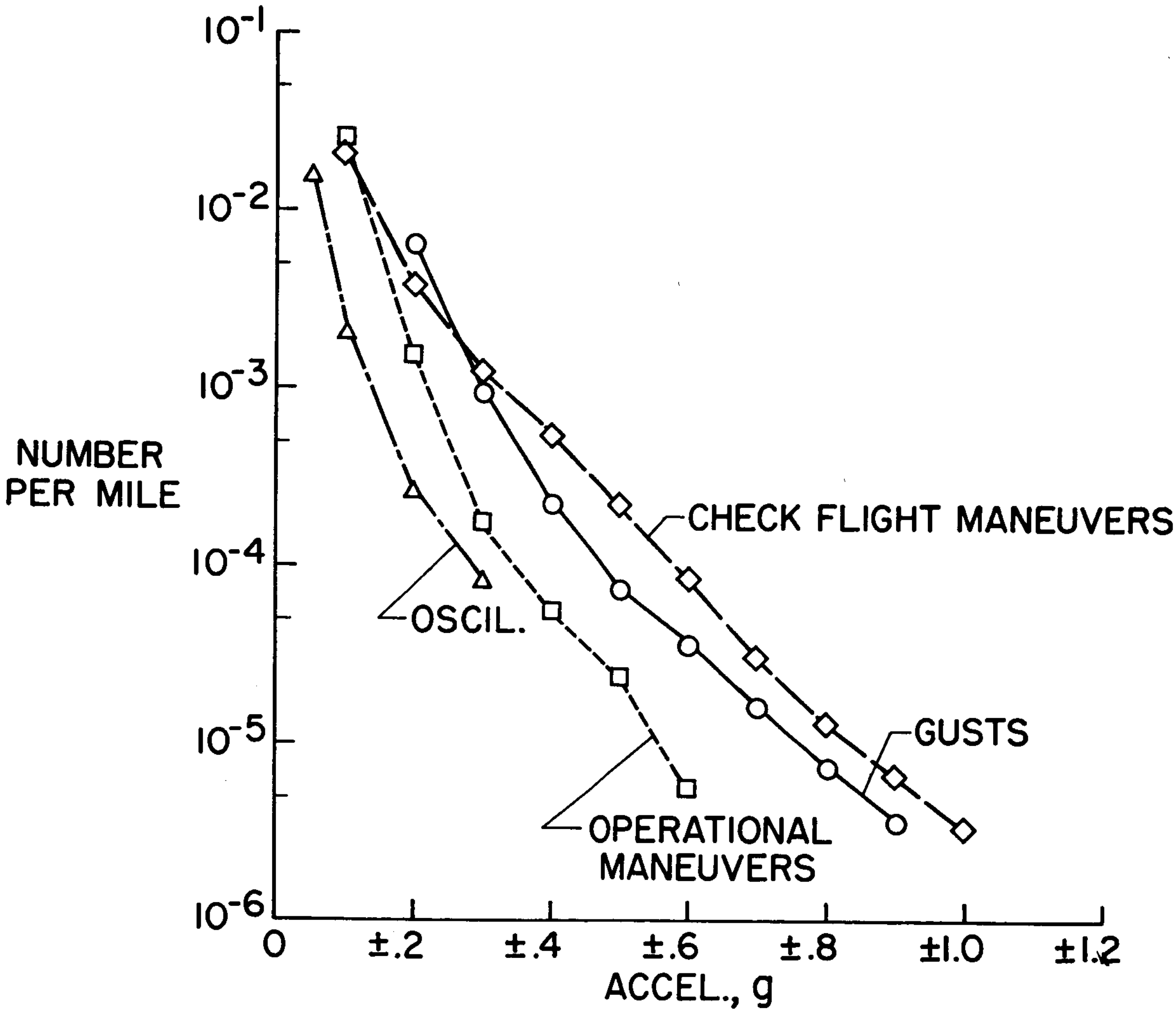

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Figure 13.- Comparison of load sources on a 4-engine turbojet transport airplane.

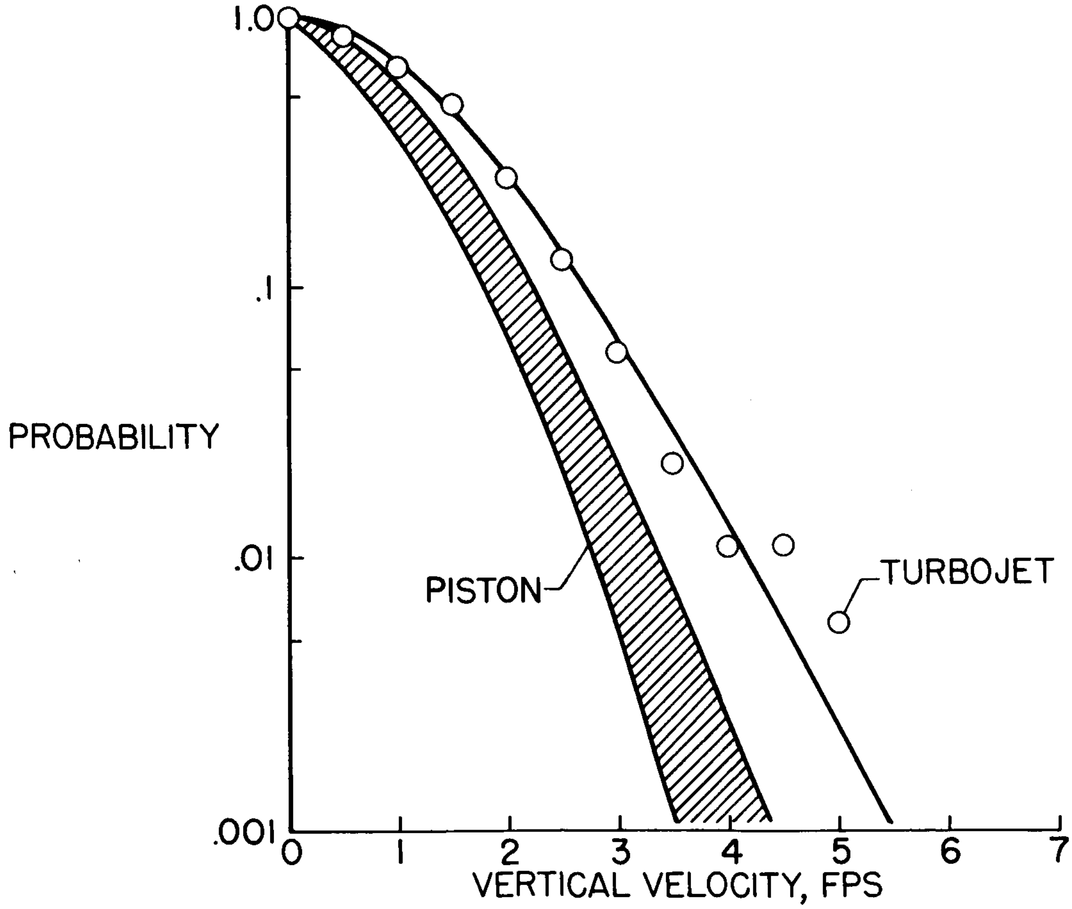

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Figure 14.- Probability distribution of vertical velocity at landing.

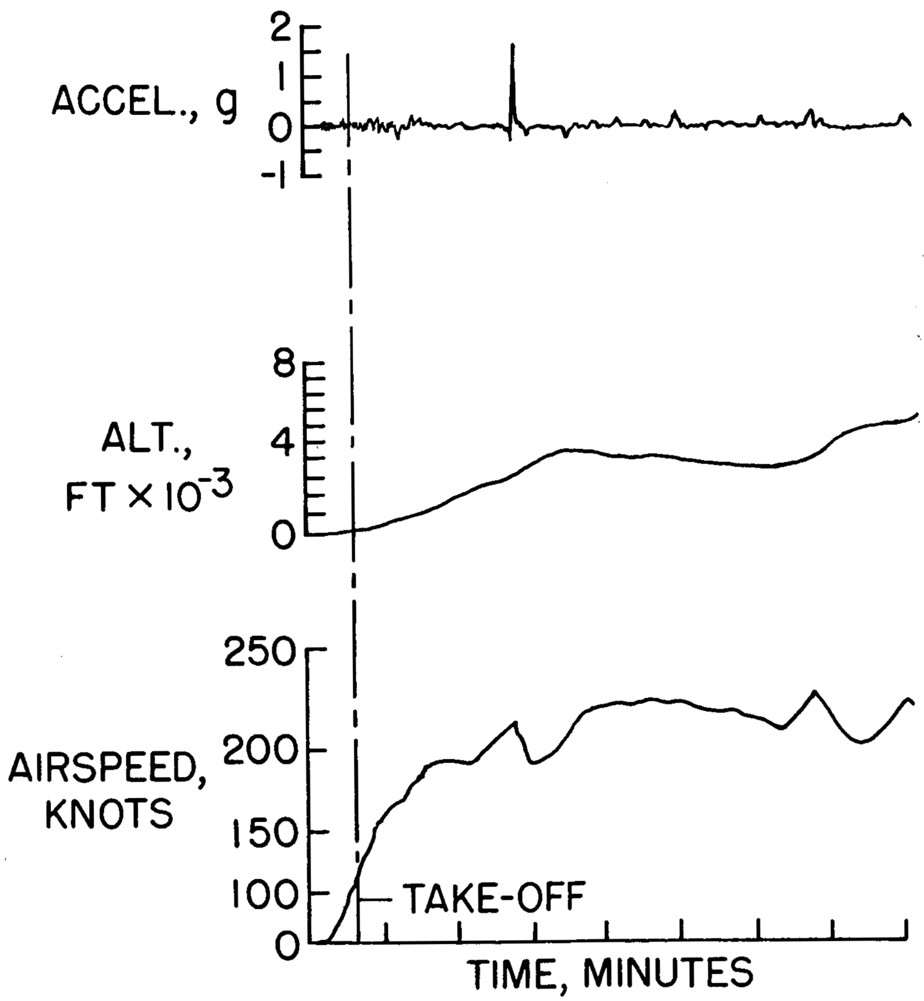

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Figure 15.- An abrupt maneuver during climb.